Renewable Energy xxx (2016) 1–17

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Dissipativity based distributed economic model predictive control for residential microgrids with renewable energy generation and battery energy storage

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A R T I C L E I N F O

Article history:
Received 18 February 2016
Received in revised form
1 May 2016
Accepted 4 May 2016
Available online xxx

Keywords:
Residential microgrid
Distributed economic model predictive control
Dissipativity
Distributed battery energy storage
Power market

A B S T R A C T

The combination of renewable energy generation and battery energy storage has been widely recognized as a promising solution to the problems associated with variability of renewable energy in residential microgrid. However, due to the low renewable feed-in tariffs in many countries, microgrid users are generally not motivated to install expensive battery systems if they can only be used to satisfy the objective of grid operator. From this perspective, a microgrid power market that encourages users to install batteries for energy-trading will be helpful for the deployment of batteries. For such circumstances, this paper introduces a user-driven microgrid power market. The possible pricing schemes are discussed and an illustrative price controller is presented. The potential destabilizing effect of the collective trading behavior of users is analyzed. A novel dissipativity based distributed economic model prediction control approach is proposed to allow microgrid users to optimize their own benefits while ensuring the performance and stability of the residential microgrid. A simulation study with photovoltaic energy generation and Vanadium Redox batteries is presented to illustrate the efficacy of the proposed method.

1. Introduction

In the past decade, distributed renewable energy generation systems, such as photovoltaic (PV) panels, have been increasingly installed in residential areas on a global scale. Renewable energy is widely acknowledged as a clean and sustainable energy source for electricity generation. Nonetheless, apart from their contributions to energy and environment, they also bring challenges to the stability of traditional electric grid. Due to the intermittent nature of renewable energy, distributed renewable energy systems tend to perturb the grid voltage and potentially destabilize the electric grid [1,2]. This destabilizing effect becomes much more significant with high penetration of distributed renewable energy systems. For example, degraded microgrid performance and overvoltage outages might be caused by PV variability [3,4]. One of the feasible solutions is to introduce distributed battery energy storage (BES) [5–8]. As shown in Fig. 1, in this case, each user can have a renewable energy generator (e.g., PV panels) and a BES, and as such can be an energy supplier or consumer at different time. These users form a residential microgrid. Different control strategies have been proposed to stabilize the microgrid voltage by manipulating the charging and discharging rates of BES [6–8]. The basic concern of these strategies is to filter out rapid fluctuations in the power profile of residential microgrid. Consequently, the stability of microgrid is secured. This is a technically effective solution. However, the installation of local BES can be an expensive investment for users in microgrid. Therefore, from the economic point of view, the potential benefit of installing BES by users has to be considered. In this paper, the term "user" is defined to refer to each individual resident with renewable generation and energy storage in the microgrid.

Although government policies encourage the selling of PV generated electricity to the main grid, the renewable energy feed-in tariff has been decreasing in recent years and has reached very low levels in some countries. This means the price of PV generated electricity continues to drop and this trend may not be changed in foreseeable future [9,10]. Hence, it might be very difficult for users in microgrid to cover the cost of BES only by selling PV generated electricity to the grid. In fact, the high and ever-increasing price of

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http://dx.doi.org/10.1016/j.renene.2016.05.006
0960-1481/© 2016 Published by Elsevier Ltd.

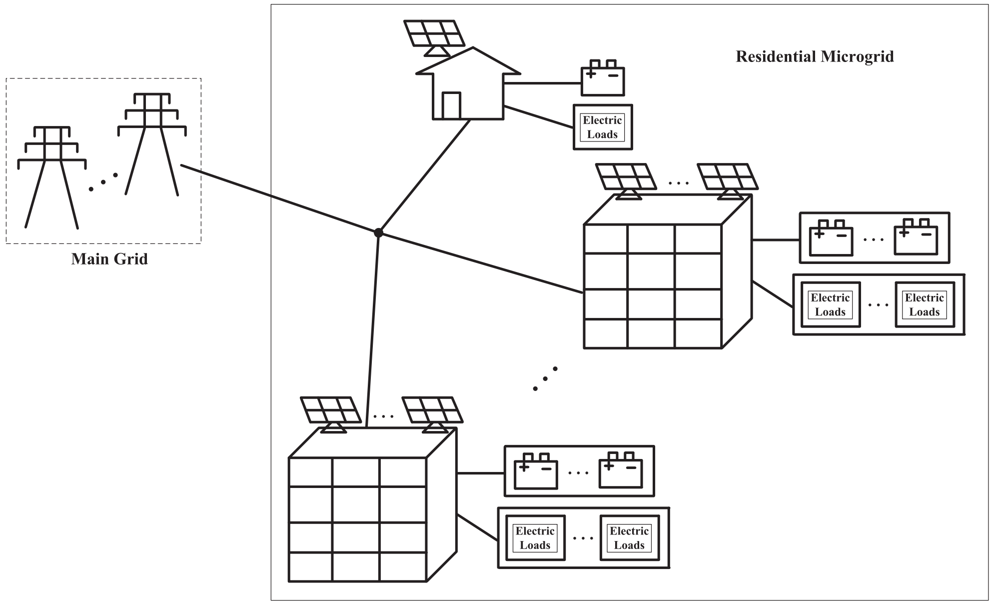

Fig. 1. Block diagram of residential microgrid consisted of distributed PV generation, BES and load.

grid electricity implies that load-leveling and energy-trading by using BES can be more profitable choices for users in microgrid [9–12]. Noticeably, there is a big gap between the prices of grid electricity and PV generated electricity in many countries, such as Australia and Italy [9–12]. This is an impediment for user's energy-trading with the grid since the cost of purchasing electricity is high and the profit of selling electricity is very low.

Undoubtedly, to facilitate and reward the energy-trading of users in microgrid, a user-driven microgrid power market (MPM) with flexible pricing scheme is necessary. The term "user-driven" implies that the proposed MPM works as a service platform on behalf of users in microgrid. Ideally, the MPM should be non-profitable and it offers fair prices to both the microgrid internal energy suppliers and the internal energy consumers in the long run. This means, on average, MPM charges microgrid internal energy consumers at a lower price and pays microgrid internal energy suppliers at a higher price compared to the main grid power market. It is obvious that such a mechanism motivates the users to install BES and to trade energy in microgrid.

A substantial amount of research work has been carried out to investigate the advantages of employing distributed BES in future smart grids [13–18]. Nevertheless, the majority of them focus on the optimization of grid operator's objectives based on main grid electricity prices [13–16]. Methods of microgrid generation control and load demand management are proposed in studies [13,14]. Unfortunately, they are not directly applicable to residential microgrid which mainly consists of variable renewable energy generations and uncontrollable loads as depicted in Fig. 1. In fact, most residential microgrids must be operated in grid-connected mode due to their dependency on electric power from the main grid. In addition, the optimization of grid operator's objective, such as operational cost reduction [13,14] or mitigation of power flow deviation from the desired trajectory [15,16], may not be desirable for users who invest in PV and BES systems. Instead, optimization of users' benefits with the market behaving in a non-profitable manner is more preferable under such circumstances.

In recent years, to facilitate the internal energy-trading in microgrid, researchers have proposed distributed control approaches based on game theory [17,18]. Their basic idea is to globally optimize the internal energy balancing of microgrids that are self-sustainable in islanded mode. Moreover, these approaches aim at obtaining global optimal performance, and thus are dependent on the solution of Nash equilibrium points as a centralized game problem. This makes the central control algorithm not scalable and can be unmanageable when the scale of the system becomes large. As it is acknowledged, the computational complexity of large scale centralized game problem can become prohibitively high due to the huge amount of subsystems. Another problem with the approaches in Refs. [17,18] is that the Nash equilibrium reached by independent controllers might be far away from the Pareto optimal solution.

In view of the afore-mentioned problems, user-driven power market and distributed control strategies should be developed for residential microgrid. At the current stage, the literature of user benefit optimization based on local power market is very scarce. To explore such systems, this paper discusses a user-driven MPM and develops a distributed economic model predictive control (DEMPC) control approach [19–23] for distributed energy storage systems in a residential microgrid. The MPM reflects market dynamics and encourages energy-trading in residential microgrid. The DEMPC approach implements a network of autonomous controllers to optimize each user's own economic interest.

In this framework, there are two levels of performance studied for the residential microgrid. At the user level, the economic benefit that each individual user achieves from the energy-trading (buying/selling) is considered. At the microgrid level, the main objective is to reduce the impact of fluctuations of both the renewable energy generation and energy consumption on the main grid, as a result of the intermittent nature of renewable energy generation and load variations. Large and rapid dynamics of power demand from the microgrid can put significant pressure on the electricity main grid, causing problems including poorer power quality and reliability, and threaten network stability. This microgrid level objective is achieved by encouraging energy trading between users so that the dynamics of the net power demand/supply to the main grid are effectively constrained. Therefore, the microgrid level performance is specified as how well the fluctuation of the microgrid-wide net power demand/supply (of all users) is

Please cite this article in press as: X. Zhang, et al., Dissipativity based distributed economic model predictive control for residential microgrids with renewable energy generation and battery energy storage, Renewable Energy (2016), http://dx.doi.org/10.1016/j.renene.2016.05.006